ANALYSIS OF VARIOUS RAPID PROTOTYPING TECHNIQUES FOR INVESTMENT CASTING

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To my parents, my dearest wife and beloved children,

Dr.CDM Elmy Johana Mohamad, Muhammad Hafiy Darwis,

Muhammad Harris Haikal, Airis Adreana and Dhiya Amanda

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ABSTRACT

Rapid prototyping (RP) technology is currently receiving huge attention as a prospective alternative to replace the conventional wax material as a master pattern in the investment casting (IC) process. This is because the RP technology allows simple to complex patterns to be fabricated directly from a computer model in a shorter time without using any hard tooling. However, quality of the RP patterns remains to be solved due to the staircase effect caused by the layered building method. Additionally, inappropriate settings of the RP parameters and the IC process variables such as pattern structure designs, shell preparation and burnout temperature may cause serious defects in the ceramic mould. This study was undertaken to investigate the use of RP patterns from three RP technologies in the IC process. These RP technologies include fused deposition modeling (FDM), multijet modeling (MJM) and 3D Printer (3DP) using acrylonitrile butadine styrene (ABS), SR200 acrylate and ZP150 powder based materials respectively. Experiments were conducted to assess the influence of the process parameters on the quality of RP patterns using design of experiment (DOE) method in order to obtain the best RP process parameters in minimizing the RP responses such as dimensional accuracy (D_A), surface roughness (S_R) and build time (B_T). In addition, the effects of the internal pattern structures on the quality of the ceramic shell moulds that are suitable for the IC process were also evaluated and analysed. Based on the results of analysis of variance (ANOVA), it was found that layer thickness (LT) and road width (RW) for FDM, LT and shell value core (SVC) for 3DP and part orientation (PO) for MJM were significant parameters affecting the D_A. Findings also showed that LT, PO, air gap (AG) and RW for FDM, PO and part position (PP) for MJM, LT and SVC for 3DP significantly affect the part S_R. It was observed that LT, raster angle (RA), PO and interaction of LT and PO for FDM, LT and PO for 3DP, PO and PP for MJM were significant parameters influencing the part B_T. Results from the main effects plot indicated that all significant parameters should be set at low level in order to obtain better D_A and S_R. In addition, all significant parameters for FDM and 3DP should be set at high level and MJM at low level to achieve faster part B_T. Empirical models for the RP responses were established based on the experimental data using the regression equation and can be readily applied to predict the respective responses. Comparing the results of different RP part internal structures and the casting parts, it was observed that the part with internal structure produces the lowest deviation of 0.006mm on D_A compared to hollow structure of 0.013mm. However internal structure had no significant effect on part S_R and at the same time also resulted in longer process time. It was also found that the optimum shell thickness of ST3, ST2 and ST1 for ABS, acrylate SR200 and ZP150 powder based materials can minimise the occurrence of shell cracking of the IC ceramic mould.

ABSTRAK

Teknologi pembuatan deras (*Rapid Prototyping* - RP) mendapat perhatian amat besar masa kini sebagai alternatif yang bakal menggantikan bahan lilin konvensional sebagai paten utama dalam proses tuangan lilin (*Investment Casting* – IC). Ini adalah kerana teknologi RP membolehkan paten yang mudah dan rumit dihasilkan secara terus daripada model komputer dalam masa yang singkat tanpa menggunakan mana-mana perkakasan keras. Walaubagaimanapun, kualiti paten RP mempunyai kekurangan yang perlu diatasi disebabkan kesan tangga berpunca dari kaedah pembinaan secara lapisan. Tambahan pula, penetapan parameter proses RP yang tidak sesuai dan pembolehubah proses IC seperti reka bentuk struktur, penyediaan cengkerang dan suhu pembakaran boleh menyebabkan kecacatan serius pada acuan seramik. Kajian ini dijalankan untuk mengkaji penggunaan paten RP daripada tiga teknologi RP dalam proses IC. Teknologi RP ini termasuk *'fused deposition modeling'* (FDM), *'multijet modeling'* (MJM), dan *'3D Printer'* (3DP) masing-masing menggunakan bahan *'acrylonitrile butadine styrene'* (ABS), *'acrylate'* SR200 dan serbuk ZP150. Eksperimen telah dijalankan untuk menilai pengaruh parameter proses terhadap kualiti paten RP dengan menggunakan kaedah Reka Bentuk Eksperimen (*Design of experiment* – DOE) untuk mendapatkan parameter proses RP yang terbaik dalam meminimumkan respon RP seperti ketepatan dimensi (*Dimensional accuracy* – D_A), kekasaran permukaan (*Surface roughness* – S_R) dan masa dibina (*Build time* – B_T). Sebagai tambahan, kesan struktur dalaman paten terhadap kualiti acuan cengkerang seramik yang sesuai untuk proses IC juga dinilai dan dianalisa. Berdasarkan keputusan analisis varian (*Analysis of variance* – ANOVA), didapati bahawa ketebalan lapisan (*Layer thickness* – LT) dan lebar jalan (*Road width* – RW) untuk FDM, LT dan nilai teras cengkerang (*Shell value core* –SVC) untuk 3DP dan orientasi bahagian (*Part orientation* – PO) untuk MJM adalah parameter yang signifikan terhadap D_A. Dapatan juga menunjukkan LT, PO, ruang udara (*Air gap* –AG) dan RW untuk FDM, PO dan posisi bahagian (*Part position* – PP) untuk MJM, LT dan SVC untuk 3DP merupakan parameter yang signifikan terhadap S_R. Diperhatikan bahawa LT, *'raster angle'* (RA), PO dan interaksi LT dan PO untuk FDM, interaksi LT dan PO untuk 3DP, interaksi PO dan PP untuk MJM adalah parameter yang signifikan terhadap bahagian B_T. Keputusan yang diperolehi daripada plot kesan utama menunjukkan semua parameter yang signifikan perlu ditetapkan pada tetapan tahap rendah untuk mendapatkan D_A dan S_R yang lebih baik. Sebagai tambahan, semua parameter yang signifikan untuk proses FDM dan 3DP perlu ditetapkan pada tahap yang tinggi dan proses MJM perlu ditetapkan pada tahap yang rendah untuk mendapatkan bahagian B_T yang lebih pantas. Model empirikal untuk setiap respon RP telah dibangunkan berdasarkan data eksperimen menggunakan persamaan regresi dan boleh terus diaplikasi untuk meramal respon berkaitan. Perbandingan keputusan berbagai stuktur dalaman untuk bahagian RP yang berbeza dan bahagian tuangan, menunjukkan bahawa bahagian yang berstruktur dalaman menghasilkan variasi yang terendah iaitu 0.006mm terhadap D_A dibandingkan dengan struktur berongga iaitu 0.013mm. Walaubagaimanapun struktur dalaman tidak memberi kesan yang signifikan keatas bahagian S_R dan disamping ianya mengambil masa proses yang lebih lama. Didapati juga ketebalan cengkerang yang optimum pada ketebalan ST3, ST2 dan ST1 untuk bahan ABS, *'acrylate'* SR200 dan serbuk ZP150 boleh mengurangkan berlakunya keretakan cengkerang bagi acuan seramik IC.

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LIST OF ABBREVIATIONS

3D	-	3D Printing
3DP	-	Three dimensional Printing
ABS	-	Acrylonitrile butadiene styrene
ANOVA	-	Analysis of variance
AM	-	Additive manufacturing
AG	-	Air gap
B_T	-	Build time
CAD	-	Computer aided design
CF	-	Castform
CMM	-	Coordinate measuring machine
CTE	-	Coefficient thermal expansion
CR	-	Cross
DIC	-	Direct investment casting
DDM	-	Direct digital manufacturing
DOE	-	Design of experiment
D_A	-	Dimensional accuracy
DTA	-	Dilatometer
FDM	-	Fused deposition modeling
H	-	Hollow
HCH	-	Hatch
IC	-	Investment casting
LM	-	Layer manufacturing
LT	-	Layer thickness
LOM	-	Laminated object manufacturing
MJM	-	Multijet modeling
MM	-	Model maker

PL	-	Part location
PO	-	Part orientation
PP	-	Part position
PS	-	Polystyrene
Ra	-	Roughness accuracy
RA	-	Raster angle
RC	-	Rapid casting
RP	-	Rapid prototyping
RM	-	Rapid manufacturing
RIC	-	Rapid investment casting
RT	-	Rapid tooling
Rv	-	Void ratio
RW	-	Road width
RTV	-	Room temperature vulcanizing
SFF	-	Solid free form
S_R	-	Surface roughness
SQ	-	Square
SLA	-	Stereolithography
SLS	-	Selective laser sintering
STL	-	Stereolithography file
SVc	-	Saturation value core
SVs	-	Saturation value shell
TGA	-	Thermogravimetric analysis
Tg	-	Glass temperature
Tm	-	Melting temperature
UV	-	Ultraviolet

LIST OF SYMBOLS

α	-	Type I error (α risk)
β	-	parameter
°C	-	degree Celcius
µ	-	Mean
µm	-	Micrometer
D	-	Desirability
k	-	regressor coefficient
K	-	Kelvin
Lo	-	Original length
R^2	-	R square
$R^2_{adj.}$	-	R square adjusted
P	-	Probability
ΔL	-	Change length in specimen
ΔT	-	Temperature change during test
ΔX	-	Dimensional deviation

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CHAPTER 1

INTRODUCTION

1.1 An Overview of Rapid Prototyping in Investment Casting

Rapid Prototyping (RP) or more commonly referred to as 3D printing technology had emerged since 1980s mainly to make prototypes for testing. Recently, the machines have been churning out an increasing number of functional products and parts after undergoing the RP revolution in many years. Furthermore, the ability of the RP can create complex parts that are traditionally difficult to manufacture has been used to print highly customized products such as medical aids and parts for aircraft engines. The RP market growth varied throughout various industrial analysis. Nevertheless, the RP market growth is expected to increase more than double from $3.1 in 2015 to $7.7B in 2020 with an estimation compound annual growth rate (CAGR) of 19.9% (Macgregor, 2015). RP products and services is also expected to increase throughout the globe as it has shown a rapid growth of 28.6% (CAGR) in 2012 to $2.204 billion. This shows an increase from $1.714 billion in 2011, with growth percentage of 29.4% (Wohler associates, 2013). According to Wohler Report, Stratasys contributed the biggest market share of 44% compared to ZCorp which is about 20.7%. Currently, an evidence of new entrants into the RP industry could be seen which results in an increase in rivalry of about 26.6% of the market share. These new entrants prove that the RP has become more acknowledged and adoption of the technology has become well known in the manufacturing process particularly in decreasing time to market and product design innovation.

Investment casting (IC) is one of the approaches to produce a better quality of near net shape metal parts that are proficient in providing a cost-effective means of mass fabrication. For that perseverance, wax master patterns are more preferable as the expandable material which can be reprocessed after dewaxing process as well as it is cost efficient. However, when it comes to intricate and multifaceted parts, the use of conventional wax patterns may result in bottleneck due to the slow processing of new pattern preparation that account over 70% of the total lead time (Pal *et al.*, 2007). It has been reported that the consequence of this conventional practice increasing the cost when relating single and low volume productions. The high overall cost has driven by the need for specialized equipment, cheap refractory and binder materials and reduction of multiple labour intensive steps of mould making. Thus, castings are typically not incorporated into the metal fabrication system until the full-scale production phase is applied. High tooling cost for hard moulding of wax pattern may not rationalise for customized single and low volume production but usually favoured for mass production (Cheah *et al.*, 2005; Vaezi *et al.*, 2011). Therefore, pattern development and process without the use of hard tools from the early inception have encouraged RP technology to be used in IC process. Currently, most of the Additive Manufacturing (AM) techniques have been employed to successfully produce IC patterns. Moreover, many Rapid Casting (RC) solutions in the IC are currently being used by various industries and researchers (Chhabra and Singh, 2011). The three basic methods used as RC solutions in Rapid Investment Casting (RIC) are shown in Figure 1.1. Approach 1 shows the RP techniques been employed directly or indirectly as a sacrificial master pattern in the IC process. For fabricating high volume IC sacrificial patterns, approach 2 is employed. Approach 3 yields direct shell production for casting from the CA model (Chhabra and Singh, 2011).

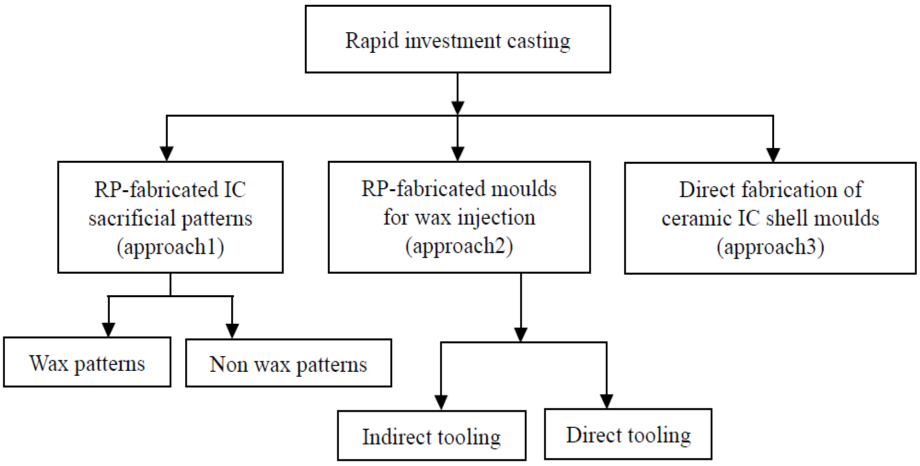

Figure 1.1: Approaches for rapid casting solutions in rapid investment casting (Chhabra and Singh, 2011)

1.2 Research Background

Generally, RP parts have been used in exchange of the traditional wax patterns, resulting in improved quality, less time consuming and cost saving. Hence, it has become crucial tool for shortening new product design and optimising cycles time. Consequently, it significantly speeds up the production lead times (Ian Gibson, 2009; Bartolo, 2011) from simulated to physical prototyping, meeting the contemporary approach to alter product development (Shan *et al.*, 2003; Xing Ai *et al.*, 2004). However, RP processes inherit low accuracy and roughness issues contributed from the staircase effect and tessellation of Computer-Aided Design (CAD) data. Warpage and shrinkage are examples of quality issues that were investigated by many researchers. Beside the slicing method, statistical tool such as Design of Experiment (DOE) and post processing method were used to obtain the best setting parameters. Thus, there are requirements to further assess the RP process parameters in the early stages due to the IC part quality is directly related to the RP master pattern fabricated from RP process. The parameters related to the RP final qualities of the parts are parts are layer thickness, raster angle, air gap, part orientation and material properties. Further evaluations through process optimization have resulted in a better RP pattern quality and shorten the production lead time.

Currently, materials such as polymer blends, paper and ceramics are being utilised to directly or indirectly fabricate the ceramic mould preparation in the RP patterns for the IC process as they have the same ability as sacrificial patterns for the IC process. Direct methods are mainly considered due to the fact that a pattern of any material either wax or non wax can be melted or burnout from the ceramic mould patterns. These include Multijet Modeling (MJM) wax and acrylate, Selective Laser Sintering (SLS) with CastForm (CF) polystyrene material or other plastics, Fused Deposition Modeling (FDM) ICW06 wax, Laminated Object Manufacturing (LOM) process and Three Dimensional Printing (3DP) wax.

RP patterns have been developed to rapidly create a mould, with varying process capabilities, lead time and varying costs known as indirect method. Room Temperature Vulcanization (RTV) silicone mould is one of most popular tool application which is considered as an indirect method proficient of replicating the IC wax patterns. Direct wax pattern showed significant advantages in saving the time, yielding almost accurate final castings with sufficient surface quality and elimination of metal tooling. Direct metal and ceramic mould fabrication are the new areas in RP. This includes RapidTool (3D Systems), direct metal laser sintering (DMLS)(EOS), and Zcast (Zcorp.) which have impacted the cost and lead times. However, the use of non wax materials such as acrylonitrile butadine styrene (ABS) from FDM, epoxy pattern from Stereolithography (SLA) and acrylate from MJM have shown major problems resulting in shell cracking during dewaxing. Therefore, the SLA process was conducted whereby the inner pattern structure was modified in order to overcome the problem (Hague and Dickens, 1995; Hague *et al.*, 2001; Hague and Dickens, 2001; Ferreira and Mateus, 2003; Tromans, 2004; Society, 2005; Norouzi *et al.*, 2009). In addition, a simple hollow geometry was proven to be better than a solid pattern construction in terms of dimensional accuracy, mould cleanliness, pattern collapsibility and resistance mould cracking (Harun *et al.*, 2009). Furthermore, especially for plastic materials, it is essential to understand the coefficient of thermal expansion (CTE) to reduce the transient thermal stress and to eliminate shell cracking (Wang *et al.,* 2010). Despite its advantages, FDM, 3DP and MJM did not provide facilities for inner design compared to SLA process. One of the primary objective, this study is conducted the different inner resin aimed at providing a process with different inner design structures.

Powder-based material from 3DP is known to produce poor surface quality with high porosity. It has been reported that polystyrene powder-based materials with high melting temperature and high melting viscosity contributes to carbonization residues due to incomplete combustion (Yang *et al.*, 2009). The application of sealants or infiltration (e.g. wax, acrylate) on porous surfaces is essential to prevent slurry penetration during shell production and throughout the dewaxing procedure. A study on the evaluation of the shell wall thickness revealed that the ZCast process has the ability of decreasing material cost and production time with different shelling strategies (Volpato and Childs, 2003). Munish Chhabra and Singh (2011) found that for Aluminum, a 5 mm shell thickness has better accuracy than 12 mm shell thickness. Most of the previous studies incorporating direct method practically used current foundry practice of shell thickness. Therefore, there is also a need to optimize the shell thickness with different zirconium size and slurry preparations.

Nowadays, a wide range of materials are available for the RP system which are very important in building the RP pattern to ensure that the IC process is more flexible, providing better precision, repeatability and lower production costs. Numerous analysis of the transient heat transfer are conducted in order to study the thermal stress inside a ceramic shell under both dewaxing (180°C) and burnout temperatures (1120°C). ABS samples reach its softening point at 105°C and 178°C while the remaining material is burned off at 575°C and above 1000°C. The Thermogravimetric Analysis (TGA) is used to predict the thermal stability when the reduction amount of residual ash is known as it measures the amount and the rate of change in the weight of a material. Furthermore, the different thermal analysis (DTA) is utilised to analyse the decomposition of glass batch materials, crystalline phase changes, chemical reactions and glass transition temperature. In addition, it is found that thermal stress is most sensitive to the glass transition temperature, followed by CTE of plastic patterns (Wang *et al.*, 2010). Therefore, thermal expansion with different RP patterns needs to be analyzed. In contrast, the reluctance of materials in thermal expansion prediction will bring about the vital view in order to get the best burning temperature of this study.

1.3 Problem Statements

The need to establish a successful inhibiting or suitable process parameters and dewaxing operation on RP patterns is essential to overcome the staircase effect that reflects the surface quality of the final pattern. The quality property of the products fabricated by the RP process is significantly affected by the process parameters. Product manufactured by RP has variety of process parameters which affect the accuracies and part roughness individually or collectively. Only a few studies have compared and reported in detail the overall quality of IC parts produced from RP sacrificial patterns (Charmeux, 2007). Many studies conducted have evaluated the FDM and 3DP using different materials and process parameters. However, the studies on the comparison between ABS produced by FDM Prodigy Waterworks System and ZP150 Powder based material are still limited. Furthermore, there is still a lack of literature on the evaluation of qualities for acrylate droplet concept (Cazón *et al.*, 2014) especially on MJM for Visijet. Conventional IC patterns made from commercial wax have the properties that limit their application on precision casting especially for the parts with thin geometries that are easily broke or deformed conventionally when handled or dipped in the refractory slurry (Wang *et al.*, 2010). Despite the many benefits of Rapid Prototyping and Tooling (RP&T) techniques, rapid tooling is still lacking in terms of quality and performance compared to conventional tooling. Thus, further research needs to be done on issues of dimensional accuracy and surface quality (Cheah *et al.*, 2005). In addition, in order to ensure the quality of the final casting, residues after the burnout process should be minimized. Most of wax patterns leave a very low ash content after

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